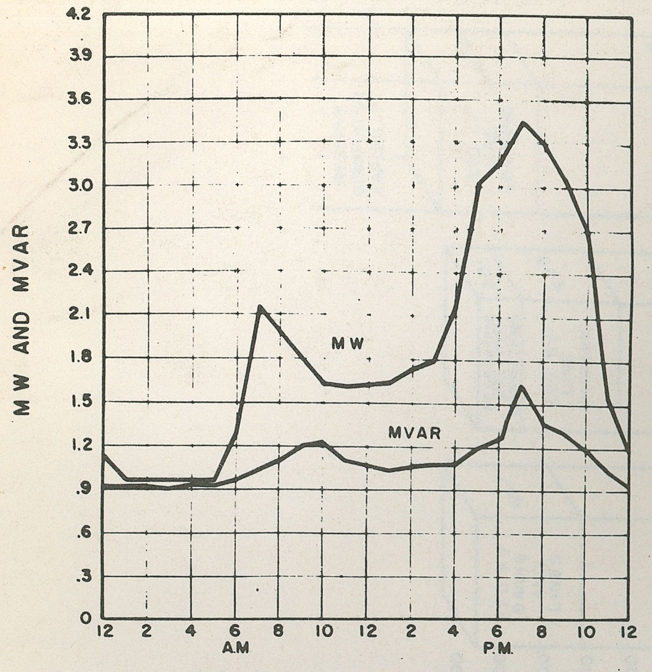

Fig. 6. Megawatt and megavar demand, substation serving residential load

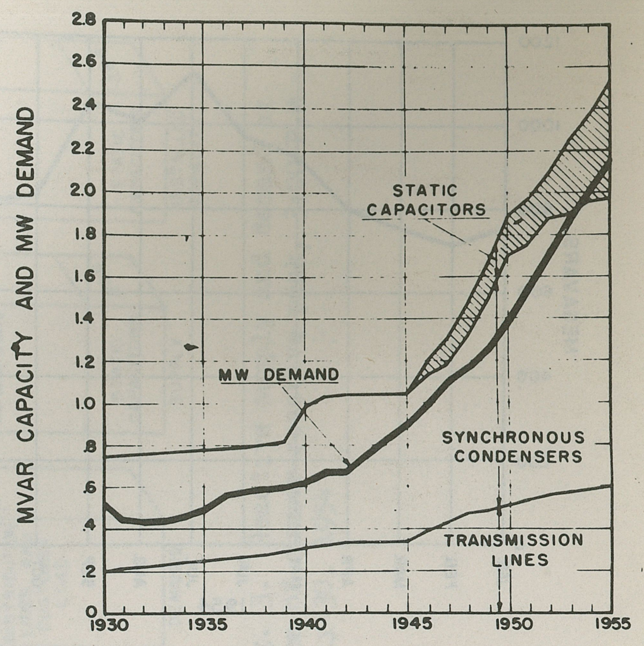

Fig. 8. Relationship between megavar capacity and megawatt demand

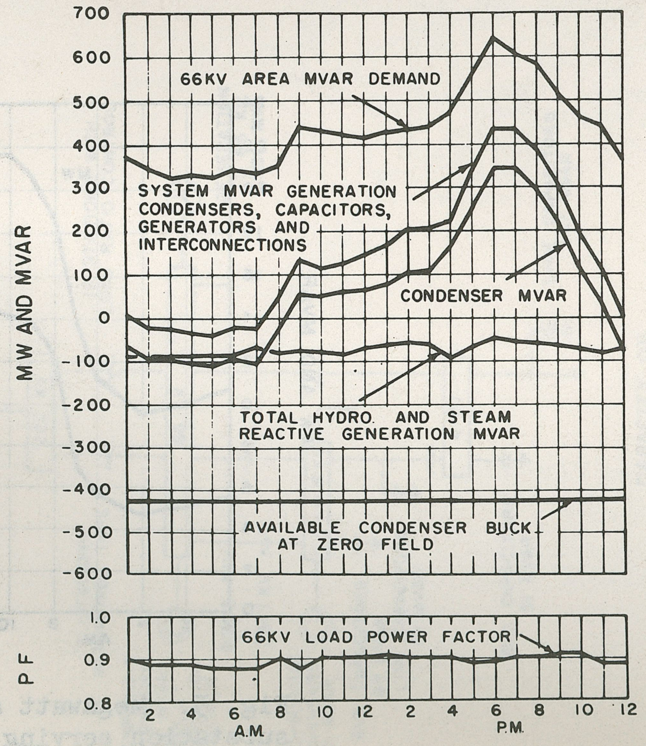

Fig. 7. Annual minimum system reactive demand by hours, Sunday, January 24, 1954

Mr Vore

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PLANNING KILOVARS AND CAPACITORS FOR THE SOUTHERN CALIFORNIA EDISON SYSTEM

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PLANNING KILOVARS AND CAPACITORS FOR THE SOUTHERN CALIFORNIA EDISON SYSTEM

J. H. Drake G. A. Davis

INTRODUCTION

Effective kilovar planning, which in reality is becoming capacitor planning for many electrical systems, requires detailed knowledge of system reactive power characteristics and operating requirements. The Southern California Edison Company system is equipped with kilovar meters in a manner which makes it possible to analyze peak and minimum system load kilovar requirements at the transmission and subtransmission voltage levels in the same manner that kilowatt requirements are analyzed. Planning kilovar generating capacity additions to insure correct bulk transmission voltage levels then becomes analogous to planning kilowatt generating capacity. In both instances load is forecast and an appropriate reserve should be carried for system contingencies.

The Edison transmission system illustrated in Fig. 1. consists of 1,913 circuit miles of 220-kv line located in Central California, Southern California and Southern Nevada. The bulk of the load comprising the two million kilowatt 1954 system peak demand is located in the southern part of the system and is approximately 260 miles distant from both the Edison generators at Hoover Dam and the Company's Big Creek hydro development on the San Joaquin River. Steam capacity comprising 52% of total system kilowatt resources is located close to the load center in the southern part of the system.

The presentation which describes the procedure for planning kilovars and capacitors for the Edison system is divided into the following four headings:

1. System Reactive Power Characteristics.
2. Operation of Reactive Power Sources.
3. Planning Criteria for Reactive Power Sources.
4. Future Trends in Synchronous Condenser and Static Capacitor Installations.

SYSTEM REACTIVE POWER CHARACTERISTICS

Fig. 2. illustrates schematically the electrical location and amount of installed reactive capacity. There are 15 major sized 220/66-kv step-down substations serving 66-kv load areas which are not normally paralleled at the 66-kv voltage level. These stations in most instances are equipped with synchronous condensers and 220/66-kv transformers with tap changing under load facilities. Each of these stations is attended and all 220/66-kv banks, generating plants, 220-kv interconnections, and synchronous condensers are equipped with reactive meters. It is possible, therefore, to obtain kilovar demand of the total system as well as kilovar demand of each 66-kv area.

Fig. 3. shows reactive demand, generation and installed reactive capacity for the day of the 1954 summer reactive peak. It will be noted that the 220-kv line charging kilovars supply the major portion of the 220-kv system line and 220/66-kv transformer bank reactive losses. The average loading of the 220-kv system during this period was considerably below surge impedance loading, due in part to abnormally low loading of Edison hydro generation at Hoover Dam resulting from deficient Colorado River hydro yield. At three of the older 220/66-kv stations the transformers are equipped with fixed taps. At these locations it is seldom possible to operate the synchronous condensers at 100% capacity factor without departing from scheduled 66-kv bus voltage. A total of 163,000 kilovars of synchronous condenser capacity thus could not be utilized for transmission voltage control due to

limitations imposed by fixed tap banks. At the remaining 12 stations, which are equipped with the 220/66-kv load ratio control transformer banks, it is possible to vary condenser loading over a wide range and still maintain scheduled 66-kv voltage.

Fig. 4 shows the maximum monthly reactive load on synchronous condensers and generators for 1954. During the summer months of July, August, and September, air conditioning, pumping and refrigeration load requirements combined to produce a seasonal kilovar peak. Although the Edison Company does not have as large a proportion of temperature sensitive load as many utilities, the effect of such load in certain system areas is becoming quite evident. In the future the time of the annual system reactive peak will be increasingly influenced by temperature sensitive load and to a lesser extent by agricultural pumping.

Since the system kilovar demand is a composite of the kilovar demands of various types of loads served by the system, the nature of these individual kilovar demands has been studied by means of watt-var charts to determine characteristics and relationships with kilowatt demands. The general characteristics of the kilovar demands at distribution substations were found to conform to several broad patterns. Kilovar demands at substations serving predominately industrial type loads were found to follow closely the pattern of kilowatt demands and were observed to be maximum during the forenoon or early afternoon as shown on Fig. 5. Kilovar demands at substations serving residential loads are shown on Fig. 6. Substation kilovar demands in many instances peaked during the forenoon or early afternoon hours although the kilowatts generally peaked during the evening.

Inspection of hourly system kilovar readings confirms this pattern and shows that the period of summer maximum system reactive demand is during the day even though evening peak kilowatt load may be larger than the daytime peak. This appears logical because the higher power factor lighting load in the evening does not impose as much kilovar demand as does the relatively poor power factor industrial, agricultural pumping and temperature sensitive loads experienced during the day.

Analysis of system reactive peak readings has shown that it is possible to predict the annual increase in system kilovar demand with an accuracy comparable to that of kilowatt demand. Since total system reactive demand depends to a large extent on loading of hydro generating resources and consequent reactive losses in 220-kv transmission, estimates of kilovar demand reflecting customer load are made at the 66-kv voltage level. Table I gives results of an analysis made at the time of the annual summer reactive peak for the years 1951, 1953, and 1954. The average annual ratio of kilovar demand to kilowatt demand for the three-year period at the 66-kv level was 0.75/1 which corresponds to a power factor of 80%. The average annual increase in reactive demand at the 66-kv voltage level was 125,000 kilovars.

When substantial additions of unswitched capacitors are planned it is important to determine whether such additions will jeopardize transmission voltage control during the system minimum load period. Fig. 7. illustrates 66-kv reactive demand during a minimum load day in 1954. Also shown is reactive generation on condensers, generators and capacitors. The difference in reactive demand at the 66-kv voltage level and reactive generation represents the excess of 220-kv charging kilovars over 220-kv line and transformer bank reactive losses. The condensers located in areas served by 220/66-kv stations equipped with load ratio control have enough capacity at zero field to bring total bucking capabilities up to 425,000 kilovars. It can be concluded therefore that ample condenser capacity is available to absorb the output of approximately 300,000 more kilovars of additional unswitched capacitors on the present system without resorting to leading power factor operation at steam plants or negative condenser excitation.

OPERATION OF REACTIVE POWER SOURCES

To promote system stability and minimize transmission power losses, the sending end voltage at the distant Big Creek and Edison Hoover plants are based on hydro project load.

From the standpoint of transmission losses the optimum voltage gradient between these distant hydro sources and the load center is approximately equal to the IR drop in the transmission lines produced by the flow of real power. Fortunately voltages at the hydro projects can be maintained at maximum levels during maximum hydro generating periods to promote stability as well as reduce transmission losses. During minimum hydro generating periods the generators at Big Creek and Edison Hoover absorb approximately 130,000 kilovars generated by 220-kv transmission lines.

The Edison Company has two major ties with adjacent utilities totalling 450,000-kva capacity. These ties are not equipped with load ratio control which makes control of transmission voltage level desirable to prevent undesired reactive interchange. Southern transmission level is stabilized at 220 kv by providing the stations equipped with 220/66-kv load ratio control with condenser loading schedules. These schedules require variation of condenser loading according to a time schedule and are changed as required by the dispatcher to accommodate changing system or hydro loading conditions.

Steam plants assist in stabilizing the southern transmission voltage and are provided with voltage or reactive loading schedules which vary in accordance with the time of day. Normally these schedules cause the plants to operate near unity power factor, leaving a margin of reactive reserve available for transmission voltage control during system contingencies.

Substation capacitor operation falls into two categories: switched operation at attended and supervisory controlled stations, and automatic switched operation at non-attended stations. In general, 16-kv and 11-kv loads are served without individual feeder or bus regulation except for the area regulation at the 220/66-kv source stations as previously described. The distribution load at 4 kv is regulated with three-phase induction or step-type regulators. At attended or supervisory controlled stations the capacitors are generally placed in service from about 8:00 A.M. until after the heavy system load period in the evening to assist in supplying system kilovars. At 4-kv stations the capacitors are placed in service according to this time schedule providing 4-kv regulators do not operate in the full buck position. In the case of 11-kv or 16-kv stations, capacitors are placed in service during this period providing bus voltage does not exceed a specified upper limit. Capacitors are not operated during system light load periods unless 4-kv regulators operate in the full boost position, or if voltage is below a specified lower limit in the case of 11-kv or 16-kv stations.

Automatic switching of capacitors at non-attended stations to obtain the same results presents a problem. Voltage control was originally used for automatic switching but this method of control did not prove satisfactory in many instances. One problem complicating automatic switching is the system practice of raising the 66-kv voltage level at 220/66-kv source stations from as low as 65 kv during minimum area load periods to as high as 69 kv during heavy load periods to compensate for regulation in 66-kv lines and step-down banks. The result is that voltage is maintained at a higher level at peak-load periods than at off-peak periods at many distribution stations, thereby making voltage control impractical. A current bias voltage control has since been developed to overcome this limitation. This method of switching utilizes a relay which is sensitive to both current and voltage. The control is in general set to be more responsive to current than to voltage. A control setting is made, in so far as practicable, to switch the capacitors on at about 8:00 A.M. and off after the station evening peak. Control operation is reviewed periodically to determine if changed station load or voltage conditions have modified desired results.

PLANNING CRITERIA FOR REACTIVE POWER SOURCES

It has been shown that at the present, annual growth in reactive demand at the 66-kv voltage level is 125,000 kilovars, and for the total system including 220-kv transmission is 140,000 kilovars. In addition to forecasting reactive load, it is necessary that consideration be given to the appropriate reserve required for contingencies prior to planning detailed reactive generating capacity additions to the system.

It is generally known that a transmission line operated at surge impedance loading has zero reactive requirement. Surge impedance loading for Edison 220-kv transmission lines is approximately 121,000 kilowatts and the lines terminating at the Hoover and Big Creek hydro plants are loaded to approximately this value. If line loadings are increased above this value, reactive requirement of the line increases rapidly. For instance, one kilovar is required for each two kilowatts of load added to a 100 mile, 220-kv transmission line initially operated near surge impedance loading.

Contingencies requiring reserve reactive capacity for maintenance of 220-kv transmission voltage levels are as follows:

1. Transmission of emergency interchange power to Edison at Magunden interconnection with the Pacific Gas and Electric Company. Calculating Board studies have shown that 170,000 kilovars of additional reactive generation is required to supply increased transmission requirements caused by full load on the interconnection.

2. Outages of long transmission lines require additional reactive generation to supply increased reactive losses occurring in remaining heavily loaded transmission lines.

3. A forced outage of a 60,000/72,000-kvar synchronous condenser.

4. Abnormally hot weather in the southern system which produces a large increase in temperature sensitive low power factor load.

Consideration should be given to the location and type of reactive generating equipment on which kilovar reserve will be carried. It is desirable to locate reactive reserve as close to the system area in need of the reactive power requirement as economic considerations permit. Transmission of reactive power over appreciable distances results in large kilovar losses and causes undesirable voltage gradients. Reserve reactive generating capacity should also be readily available to the System Dispatcher in large blocks.

Steam plants provide a source of these large blocks of reactive reserve which are readily available to the System Dispatcher. A kilovar capability constituting 1/2 of the kilowatt capability can be designed into a steam plant for approximately 1/6 of the cost per kilovar of a synchronous condenser or 1/4 that of a switched capacitor. Most Edison steam plants are normally operated near unity power factor and reactive capability is used during emergencies to maintain desired 220-kv voltage levels. Reserve reactive capacity is also carried on synchronous condensers located at major substations along the Big Creek transmission system.

Reactive capacity is installed in each 66-kv area in amounts sufficient to permit scheduled 66-kv bus voltage to be maintained during a forced or planned outage of the largest synchronous condenser in the area. At 220/66-kv stations equipped with load ratio control transformer banks, area reactive demand is reviewed annually to insure that the voltage rise margin available with load ratio control is sufficient to compensate for increased voltage drop in the transformer banks caused by outage of a large condenser. At 220/66-kv stations with fixed transformer bank taps, condensers are normally operated with a sufficient margin to permit bus voltage levels to be maintained during a condenser outage.

Smaller sized synchronous condensers are located at a few of the older distribution substations, but in general the reactive generation at the distribution substation levels and on the distribution circuits is provided by static capacitors.

The use of static capacitors for reactive generation accomplishes two purposes. One of the purposes is to provide required system reactive power as has been discussed. The other purpose is to provide local voltage increases and ampere reduction for components of the distribution system. This versatility, as well as lower cost when contrasted to synchronous condensers, explains why the use of capacitors on the Edison system has been greatly expanded during the post-war years.

Unswitched capacitors are programmed for installation on all 4-kv circuits in amounts sufficient to result in approximately unity power factor operation on circuits during light load periods. Installations on each circuit total about 20-25% of circuit peak kva demand. In areas of high air conditioning density this figure can be larger. Largest sized individual installation in service on a 4-kv circuit is 300 kva. Since 4-kv circuits are voltage regulated, relatively few switched 4-kv installations are proposed, and these are for local voltage correction only.

Similar programs are being formulated for fixed capacitor installations on 12-kv circuits in higher distribution voltage areas. Larger sized automatically switched 12-kv installations, up to 750 kva at each location, are installed in agricultural and industrial areas to correct local voltage regulation problems. Switched installations, up to 1,200 kva at each location, have been recently installed on 16-kv lines for local voltage correction.

Fixed three-phase secondary capacitors have been proposed to a limited extent on secondaries of large power and pumping installations serving poor power factor loads. Fixed secondary capacitors are also in service in the secondary network area. Single-phase secondary capacitors are now being applied in residential areas of high air conditioning density.

Certain of the 66-kv operating areas are known to be deficient in reactive generating capacity or are faced with voltage problems due to long subtransmission or distribution lines. The installation of substantial amounts of switched capacitors on substation busses in these areas has been accomplished at lower cost than installation of additional synchronous condensers at either bulk transmission or distribution load centers. First priority in the deficient areas is given to installations at 4-kv substations served by 12-kv or 16-kv lines where voltage regulation conditions are most likely to require correction, and at stations where transformers are operating on the lowest transformation ratio. Size of capacitor banks are established on 4-kv busses in half rack 750-kva or full rack 1,500-kva increments based on desired voltage correction and transformer bank size.

First priority for capacitor banks at 66-kv step-down stations is given to stations which require voltage regulation correction or which are operated on lowest transformation ratio. These stations are usually remote from the 220/66-kv source stations and are usually in areas with insufficient reactive capacity. Size of capacitor banks are normally made in full rack 1,500-kva increments and largest installation to date is 4,500 kva. Direct installations of capacitors on 33-kv or 66-kv busses at similar remote locations will be the next step in the application of capacitors.

Series capacitor installations are limited to two locations on higher voltage distribution circuits. None are contemplated for transmission line use at this time.

The extent to which static capacitors have assumed a share of the total system reactive generation is shown on Fig. 8. The first installations were in 1945 at which time the system demand was about 1,100,000 kilowatts. By the end of 1955, about 500,000 kilovars of capacitors will have been installed for an estimated system demand of 2,150,000 kilowatts.

FUTURE TRENDS IN SYNCHRONOUS CONDENSER AND STATIC CAPACITOR INSTALLATIONS

The future trends as to reactive generating sources are expected to follow the pattern established during the last several years by continuing the installation of large annual increments of static capacitors to supply the bulk of reactive load growth. Synchronous condenser installations, which for many years kept pace with reactive load growth and which provided reactive reserve, will in the future decline in relative importance since fewer long transmission lines which require kilovar absorbing capability will be added.

The major portion of the capacitors supplying the 125,000 kilovars of annual 66-kv reactive load growth will be apportioned to the various 66-kv subtransmission areas in accordance with the reactive requirements of the areas. Exact locations will depend on available transformer taps, on desired voltage correction and other factors determined by calculating board studies.

First priority for capacitor additions will continue to be for unswitched installations on distribution circuits for unity power factor operation during light load periods. Switched circuit additions will be predominately for local voltage control only on 12-kv and 16-kv circuits.

First priority for capacitors at substations will be on the low voltage busses at 12/4-kv and 16/4-kv locations which require voltage correction or which are operating on lowest transformation ratio. Next in order of priority will be low voltage bus installations at 66/4-kv, 66/12-kv, and 66/16-kv substations requiring similar correction. Emphasis will be placed at locations in the 220/66-kv operating areas which are deficient in reactive generating capability. At attended stations these installations will continue to be switched manually. At unattended stations switching will be by supervisory control whenever possible, and otherwise by means of current biased voltage control.

Future reactive generating capacity necessary to support the 66-kv subtransmission system at locations remote from 220/66-kv sources will probably consist of substantial blocks of switched capacitors connected to the 66-kv busses at these outlying stations. These installations will be manually or supervisory controlled. These large capacitor banks on the 66-kv busses will be in lieu of the past practice of installing smaller sized synchronous condensers at the outlying stations or of installing larger sized condensers at the 220/66-kv sources to support the 66-kv subtransmission system.

It is probable that there will be few future installations of reactive generating capacity at the 220/66-kv substations. These few installations could consist of substantial blocks of switched capacitors operated directly on the 66-kv bus instead of additional synchronous condensers. At such locations where synchronous condensers are already in service, the switched capacitors can be in large blocks and still provide smooth voltage control. At locations without synchronous condensers, the size of switched capacitor blocks will depend upon size of the existing 220/66-kv load ratio control transformer steps.

Future steam stations located close to the southern load areas will provide the reactive reserve which was previously provided by synchronous condensers.

CONCLUSION

1. The Southern California Edison Company system is equipped with reactive meters in a manner which makes it possible to study system kilovar characteristics in the same manner that kilowatt characteristics are studied. Experience has shown that it is possible to predict the annual increase in system kilovar demand with an accuracy comparable to that of kilowatt demand. The increase in system reactive demand is about 125,000 kilovars annually based on the present rate of system growth.

2. System contingencies requiring reserve reactive capacity should be considered in kilovar planning. Steam plants provide an excellent source of reactive reserve which

is readily available in large blocks. Furthermore, reactive reserve capability can be designed into a steam plant at a relatively low cost when contrasted to the cost of providing such a reserve by means of capacitors or synchronous condensers.

3. The use of 220/66-kv load ratio control transformers provides maximum operating flexibility. With facilities of this type it is possible to operate synchronous condensers at 220/66-kv stations at 100% capacity factor and at the same time maintain required 66-kv voltage schedules over a wide range.

4. Increased reactive demands in the past have largely been supplied by installations of synchronous condensers or by line charging kilovars furnished by additional long transmission lines. Future increases in reactive demands due to load growth will be supplied for the most part by additional capacitor installations at distribution stations or on distribution circuits. In the future relatively large blocks of switched capacitors may also be installed on 66-kv busses at distribution substations located in the 66-kv load areas to support the 66-kv system. Relatively few future installations of reactive generation are anticipated at 220/66-kv source stations.

- - -

TABLE I

ANALYSIS OF SYSTEM REACTIVE REQUIREMENTS 1951-1954

	11:00/a July 20 1951	2:00/p July 22 1953	3:00/p July 30 1954	Average Annual Increase 1951-1954
Synchronous Condensers	778	937	910	
Static capacitors	185	262	366	
Generating Plants	100	174	208	
D.W. & P. at Laguna Bell	0	25	2	
P.G. & E. at Magunden	0	-18*	-31*	
M.W.D. at Highgrove	0	0	22	
Total reactive generation for Edison (MVARS)	1,063	1,380	1,477	145
Edison net load at Generation (MW)	1,436	1,709	1,829	131
Total System var/watt ratio	.74	.81	.81	
Total load area reactive requirements at 66-kv voltage level	992	1,237	1,366	125
Total megawatt requirements at 66-kv voltage level	1,390	1,639	1,767	126
66-kv var/watt ratio	.71	.76	.77	

* Minus sign indicates reactive flow from Edison

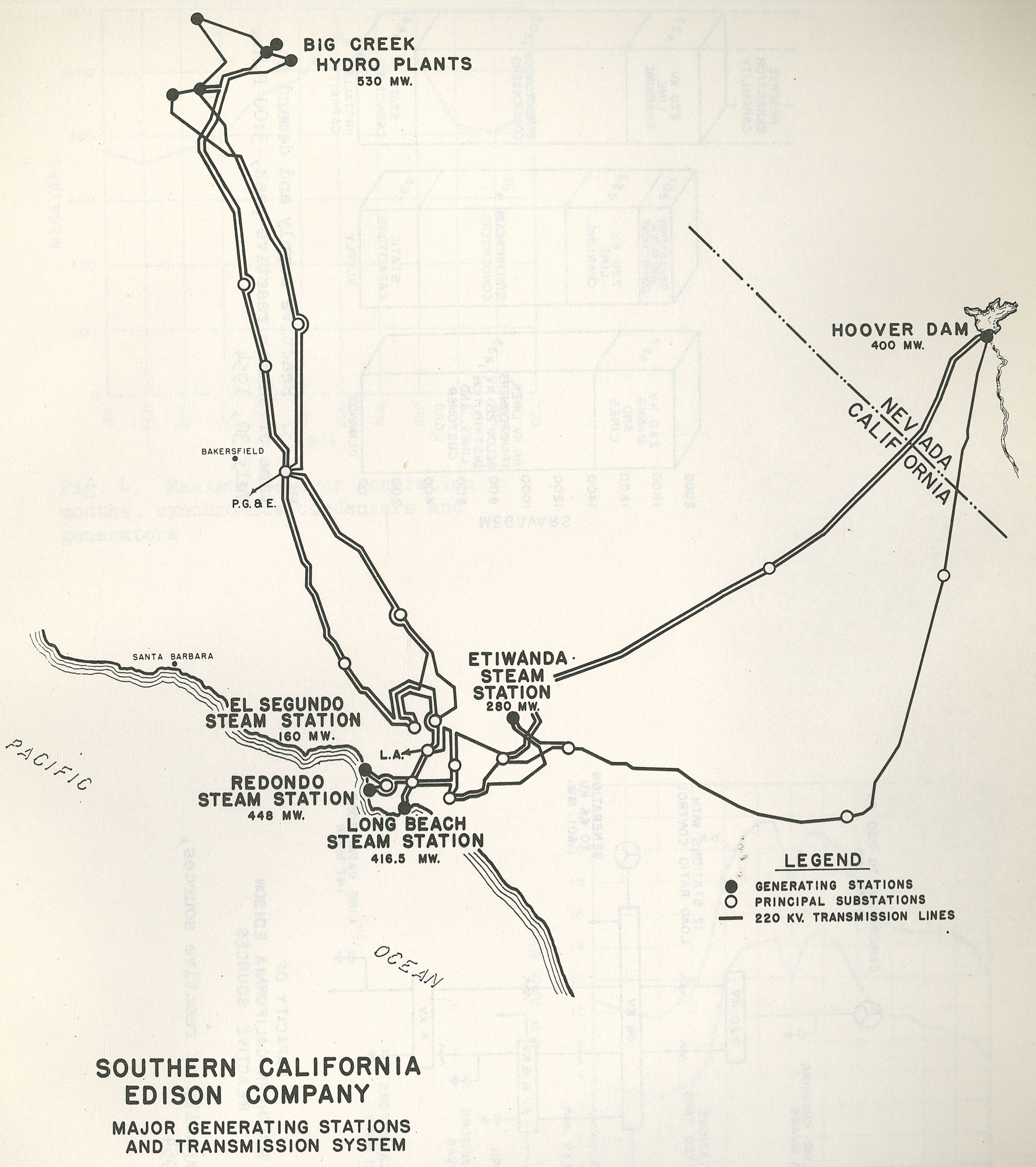

Fig. 1. Major generating stations and transmission system

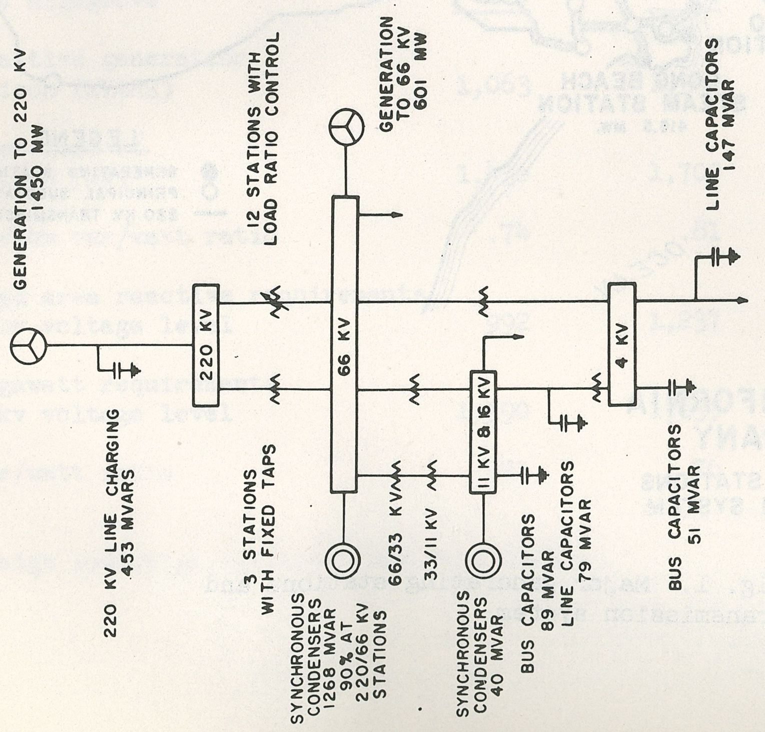

Fig. 2. Capacity of reactive sources, July 30, 1954

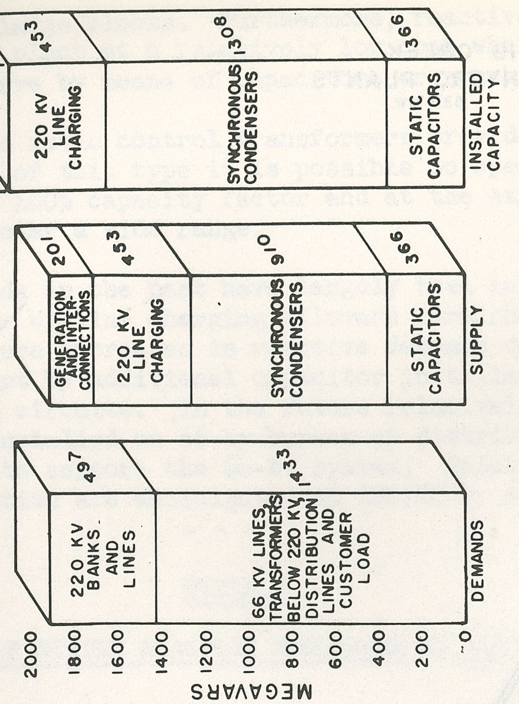

Fig. 3. Reactive supply and demand at time of summer reactive peak, 3:00 P.M., July 30, 1954

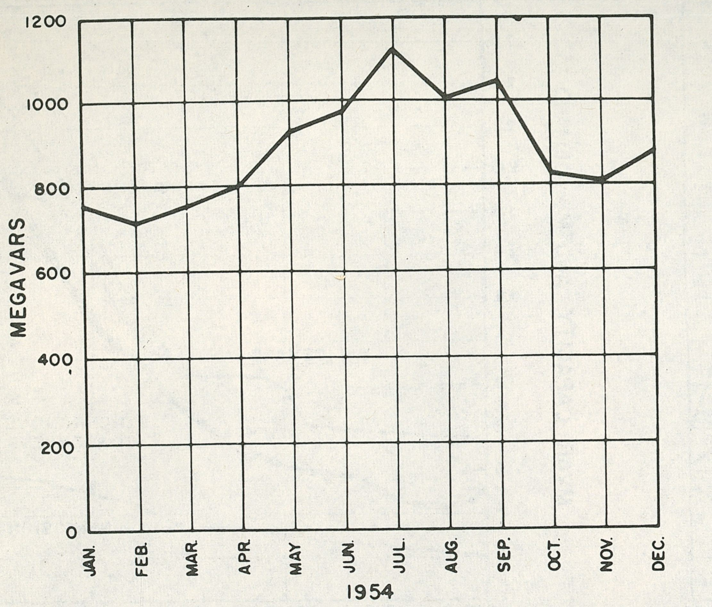

Fig. 4. Maximum megavar generation by months, synchronous condensers and generators

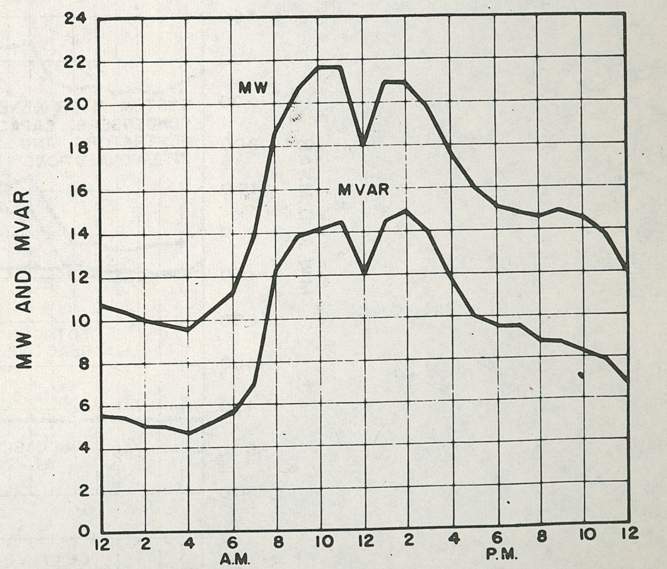

Fig. 5. Megawatt and megavar demand, substation serving industrial load

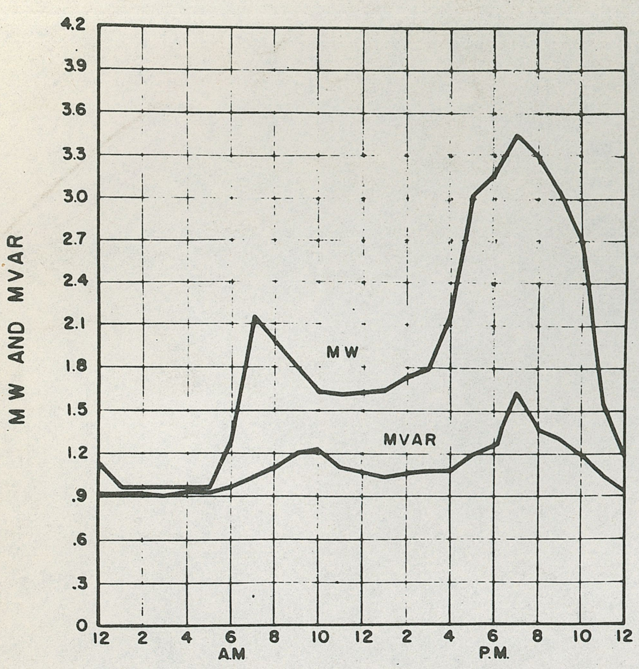

Fig. 6. Megawatt and megavar demand, substation serving residential load

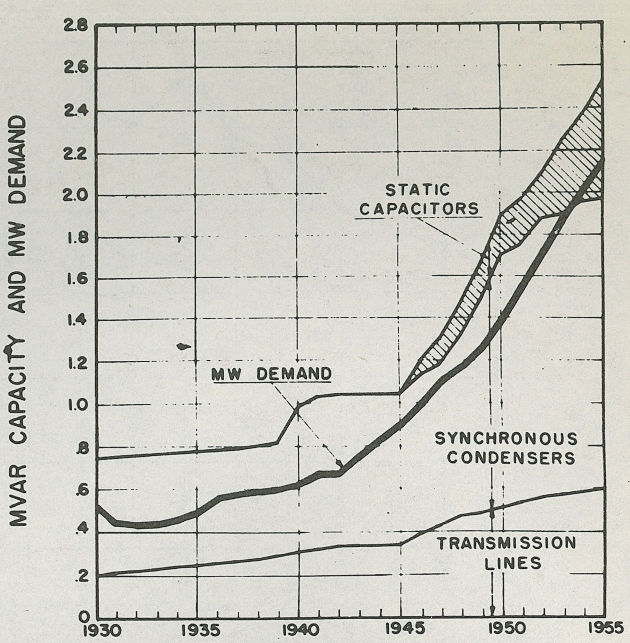

Fig. 8. Relationship between megavar capacity and megawatt demand

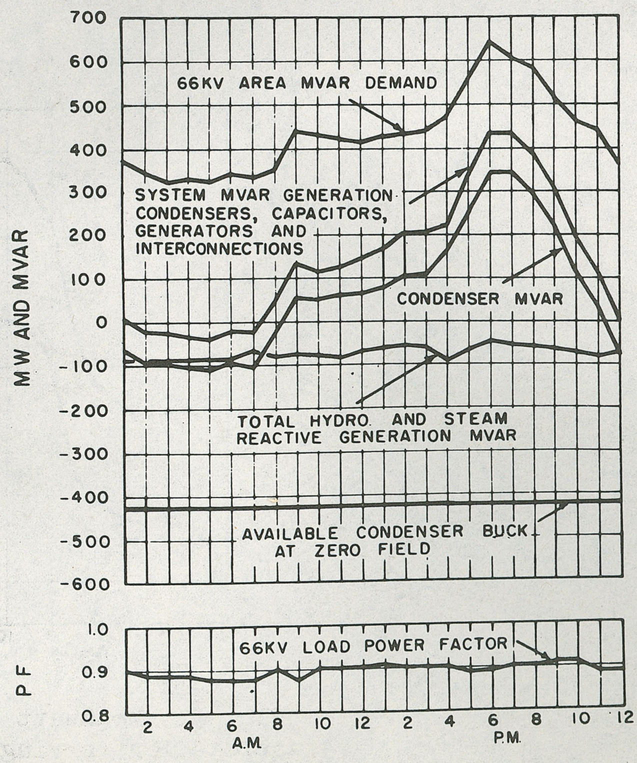

Fig. 7. Annual minimum system reactive demand by hours, Sunday, January 24, 1954

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